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RESEARCH PROJECT INITIATION

Date: November 24, 1975

Project Title: Continued Development and Application of Some Fast Neutron Dosimetry Techniques Utilizing Plastic Track Detectors for Therapy & Health Physics

Project No: E-26-620 (Continuation of E-26-613)

Principal Investigator: Dr. K. Z. Morgan/Mr. M. Schrenk

Sponsor: Energy Research & Development Admin., Oak Ridge Operations, Oak Ridge, Tenn. 37830

Agreement Period: From 9/1/75 Until 8/31/75

Type Agreement: Contract No. E(40-1)-4814 Modification No. 1

Amount: $33,500

Reports Required: Publication Preprints; Publication Reprints; Annual Progress Report; Final Report.

Sponsor Contact Person (s):

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No budget sheet yet

Assigned to: Nuclear Engineering

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SPONSORED PROJECT TERMINATION

Date: April 27, 1977

Project Title: Continued Development & Application of Some Fast Neutron Dosimetry Techniques Utilizing Plastic Track Detectors for Therapy & Health Physics

Project No: E-26-620

Project Director: Dr. K. Z. Morgan

Sponsor: ERDA; Oak Ridge Operations; Oak Ridge, TN 37830

Effective Termination Date: August 31, 1976

Clearance of Accounting Charges: August 31, 1976

Grant/Contract Closeout Actions Remaining:

- _ Final Invoice and Closing Documents
- _ Final Fiscal Report
- _ Final Report of Inventions (Annually an Interim Patent Report, positive or negative, is required)
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- _ Classified Material Certificate
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NOTE: CONTINUED AS E-26-623

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CA—4 (3/76)

E-26-620

PROGRESS REPORT

Development and Application of the Electrochemical Track Etching Techniques

(Contract No. E-(40-1)-4814)

Counting Techniques

Two new techniques were developed to facilitate counting of the polycarbonate foils. Both techniques employ optical devices almost every laboratory and university possess in readily obtainable supply - the microfiche reader and the overhead (transparency) projector. These two techniques offer several advantages over the microscope for low count density and thick foils. (Spark counting requires very thin foils and techniques such as densitometry measurements require a large number of counts - high dose). Advantages effected during utilization of these two techniques over our earlier conventional microscope counting are:

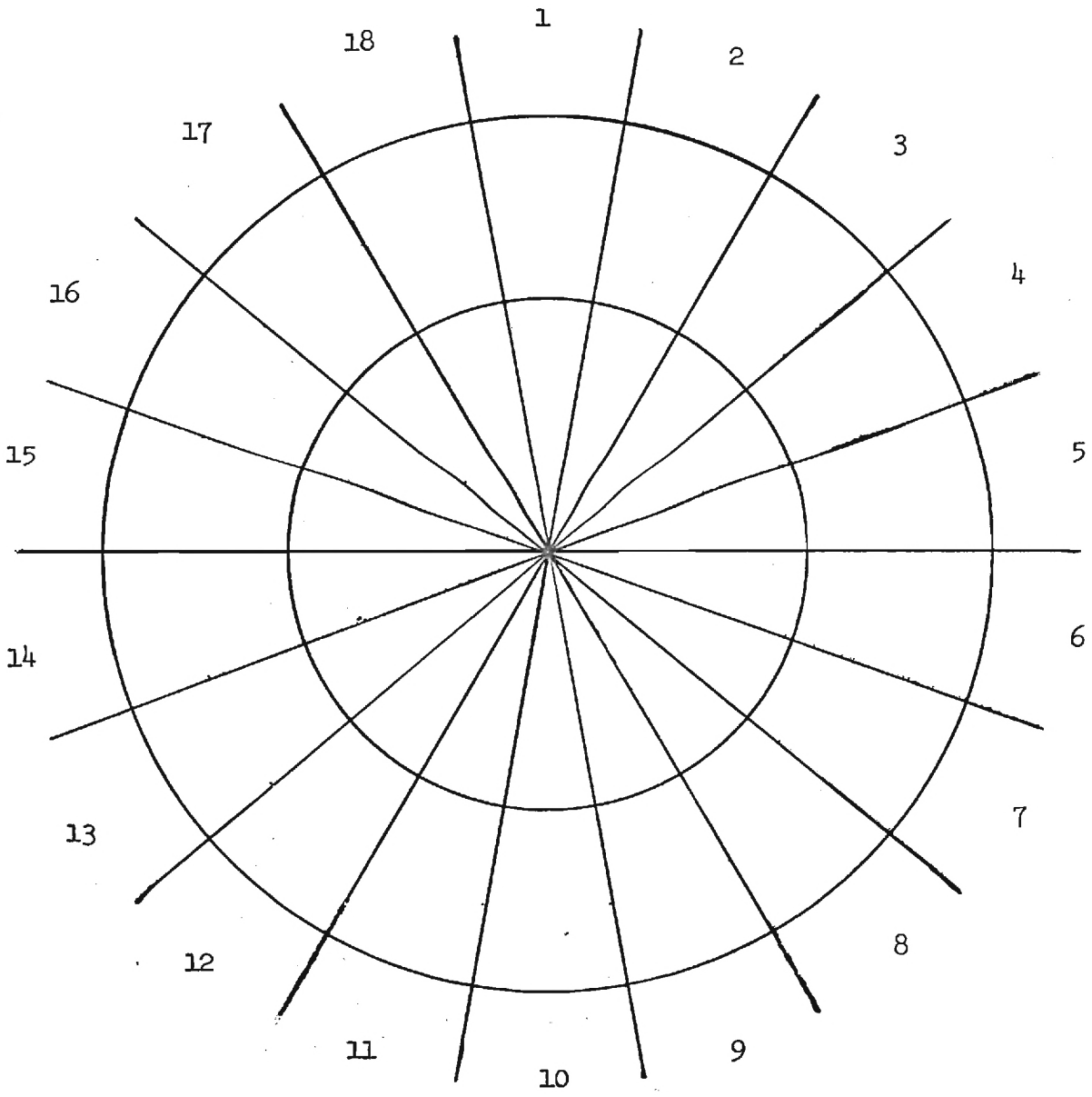
1. A larger foil area is actually counted; the overhead projector providing greatest viewing area, microfiche reader second, and microscope third.
2. Image is viewed on a screen and not through an eyepiece causing less eye strain.
3. Less time is required per foil for counting.
4. No elaborate equipment is required other than these inexpensive pieces of equipment most institutions possess anyway.

To facilitate counting with the transparency projector a grid was

constructed on the screen upon which the image was projected, Figure I. The grid consisted of two concentric circles of radius 4.3 and 7.0 cm on the screen which were cut into sectors with radii drawn every 20^{o} (18 total). This yielded 36 small areas which could be counted easily, their sum equalling the total number of counts contained within the enclosed area, $154cm^{2}$. The counts appear on the screen as black dots on a clear background so the viewer encounters little difficulty in recognizing them.

Figure II is a photograph of the screen of the overhead projector with the image of a foil containing high background projected upon it. The number of counts obtained for this foil within the encircled area was 685 counts. This number was obtained by counting the tracks within the $154cm^{2}$ circular area, then making a random movement of the foil (so a different area of the foil was superimposed over the grid), recounting the number of tracks and finally, calculating a numerical average of these two trials. Foil magnification was 14 x with a screen to projector distance of 16 ft. 5 in. and track diameters were about 0.6mm. Of course, almost any magnification could be obtained depending on the distance of separation of the projector and screen.

The second technique developed - the microfiche reader - offers other possibilities. Figure III is a photograph of a small rectangular portion of the microfiche reader screen. The actual area of the screen photographed was 17 by 13cm and the foil shown is again a background foil. The horizontal line traversing the upper section of the photograph is a component of the "cross-hair" placed upon the microfiche reader screen to partition the screen into quarters and thereby facilitate counting. Foil magnification here was 50 x and track diameters were in the range of 2-4mm. The foil shown yielded 142 counts. This value was obtained by counting one



GRID USED IN FOIL COUNTING

Figure I

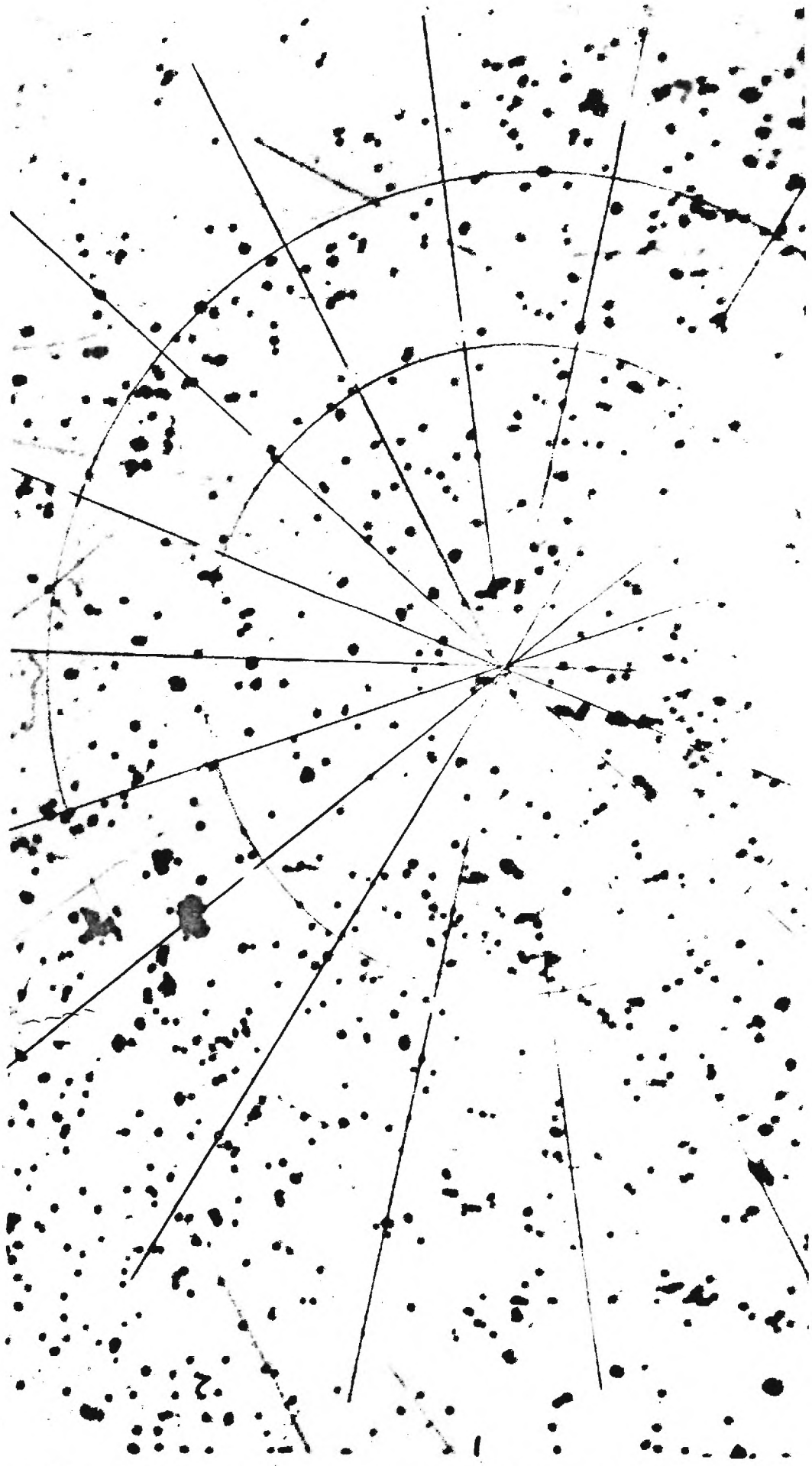


Figure II - Photograph of Transparency Projector Screen Showing High Background Foil

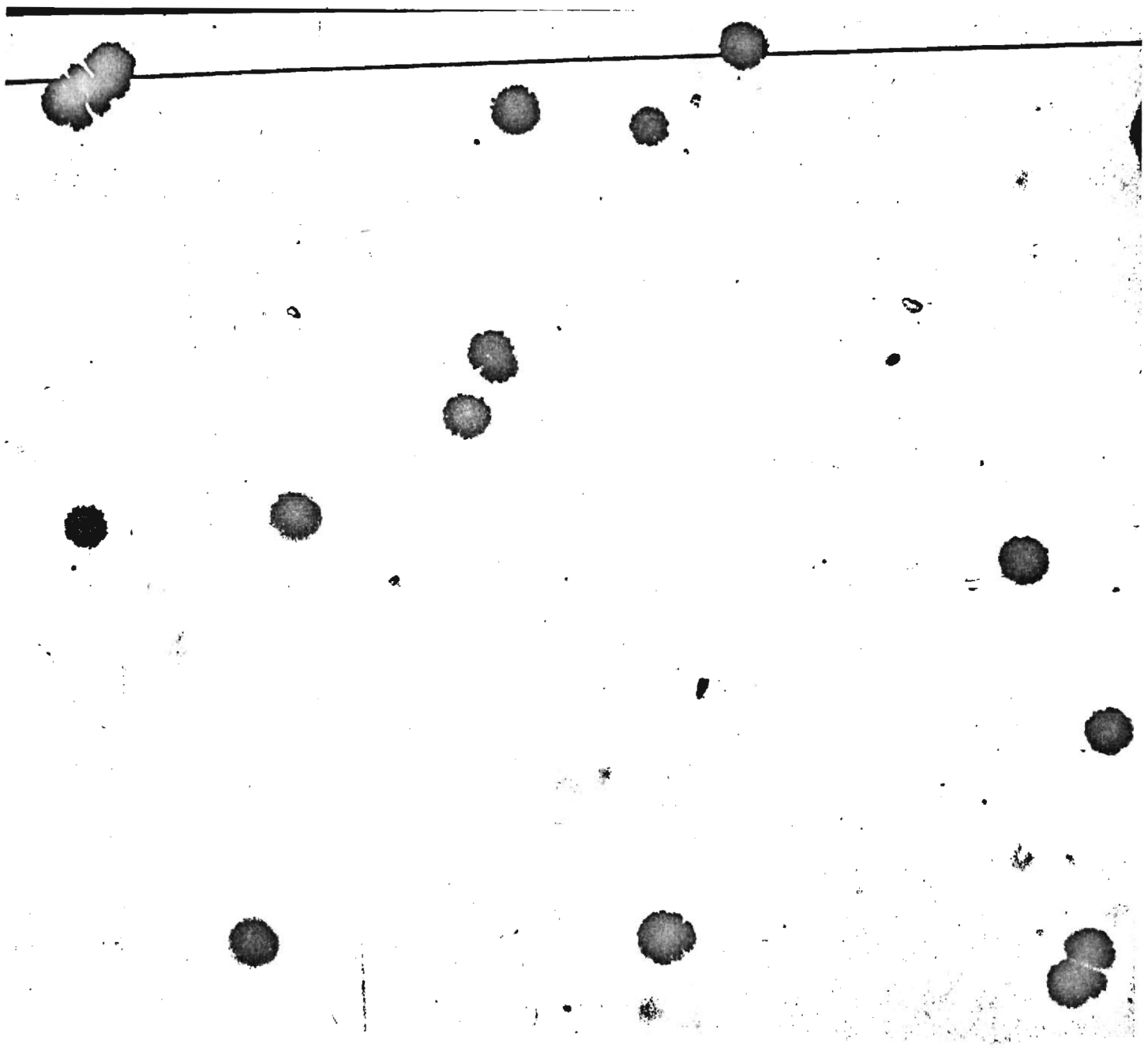


Figure III - Photograph of 17x13cm Area On Microfiche Reader Screen
Showing Background Foil

quarter of the screen, then moving the foil in a random fashion and recounting the same screen quarter (but now a different portion of the foil would be projected beneath the cross-hairs). This procedure was repeated until four quarters were counted at which time a sum was calculated.

There is one very interesting difference between the two foils shown on Figures II and III. The first foil was used in an earlier study concerning the effect of annealing on foil background and was annealed at a temperature of 140°C for 15 minutes. The foil shown on the microfiche reader photograph, Figure III, was used in the latest background study but was actually not annealed at all (a control). Clearly the second foil (Figure III) possesses fewer stray marks and is consequently more transparent than the first foil (Figure II). If both foils are held to the light a greater degree of homogeneity in the track distribution is perceived on the second foil than the first. This difference arises because the second foil (Figure III) was washed with isopropyl alcohol and rinsed with distilled water prior to etching whereas the first foil was not washed. This process apparently removes dirt and surface abrasions which will be etched if left on the foil as indicated by the high background present on the first foil (Figure II).

Since the magnification was 50x with the microfiche reader, the tracks were viewed in greater detail than when viewed with the transparency projector. The star-like outcroppings from individual tracks became visible, similar to the appearance of the tracks seen by the microscope. Also, not unlike the case with a microscope, the focus on the microfiche reader can be adjusted so the plane of focus includes only tracks in one plane or on one side of the foil or the other. The tracks on the side opposite the side being visualized appeared as unfocused blurs. This would explain why some tracks were viewed with distinction and others were out of focus in Figure III. A smaller area of the total foil was visible on the microfiche reader screen

than on the transparency projector screen but the tracks were more readily distinguishable from other stray marks on the foil.

Work is now under way to obtain an accurate estimate of the error involved in the usage of these foil reading techniques and to determine a factor to multiply by the counted tracks to yield the total number of counts on the foil. It is felt these two techniques will speed up counting and greatly enhance the efficiency of eliciting data from the Lexan foils.

Use of Large Chamber

Another important aspect of this effort has been the attempt to bring on-line a large etching chamber capable of etching many times the number of foils our present chamber will etch (7). The new chamber will etch 35 foils. The problem up to this point has been one of leakage of the etching solution. At the onset of this undertaking (beginning of Project E-(40-1)-4814) almost half the etching positions leaked severely. The first attempt made to solve this problem culminated in the construction of a vice-like instrument to apply pressure directly on the etching positions and thereby reinforce the watertight seal. This succeeded in reducing the leakage to 3 or 4 foil positions but the upper limit had been reached as to the amount of pressure that could be applied safely to the chamber. The problem must then be arising due to another source. It was determined the recesses into which the foils fit in the chamber had small but detectable errors in their machined depths. Since the rubber O-rings covering these recesses were a standard over-the-counter size, an uneven seal might be created when these were pressed together. New O-rings were then ordered to a custom specification (not a standard size) which were constructed with

a softer material to facilitate formulation of a watertight seal when pressure was applied. This modification was successful until one foil etched through producing a short circuit. It is now felt it will be possible with a reasonable amount of further work to bring this 35 foil chamber on-line in the near future. Use of this chamber will significantly increase the number of data points (foils) obtainable per etching cycle.

Background Reduction

Several studies were undertaken to look at the effect of annealing the Lexan foils to reduce the inherent background. The most successful of the studies yielded interesting and useful results. Six groups of foils, seven to a group, were heated to various temperatures for twenty minutes. Then one foil from each group was placed in the seven foil chamber along with a control which had not been annealed and the etching process executed. Etching conditions used throughout this study were:

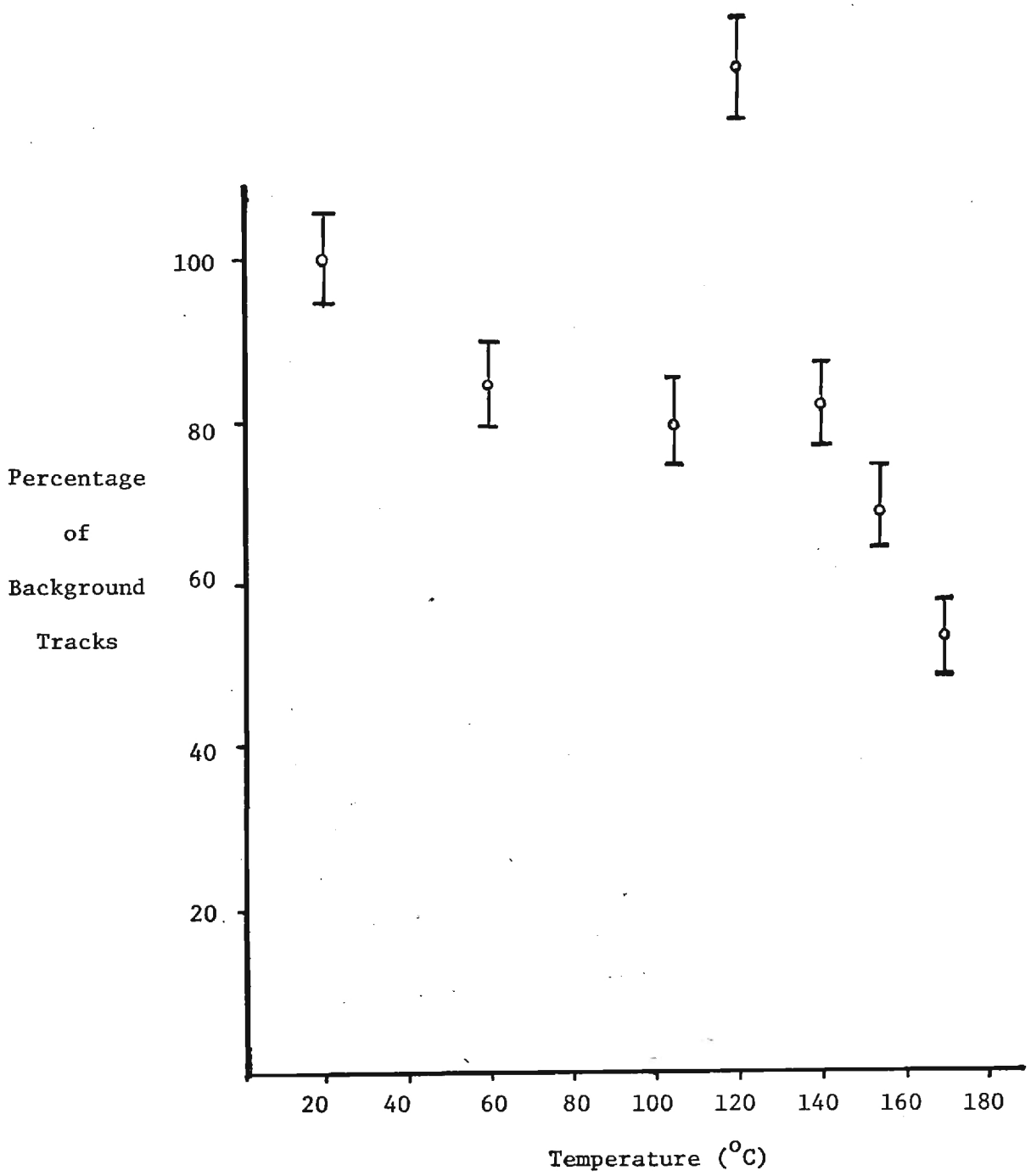
1. Etching solution - 30% KOH
2. Voltage - 700 V
3. Frequency - 2 KHz
4. Etching time - 2 hours

It was found that a significant reduction in background and increase in overall track homogeneity resulted if the foils were washed with isopropyl alcohol and rinsed with distilled water prior to annealing, as mentioned above. The foils were counted with both counting techniques described above to examine the correlation between the two methods. The six temperatures used to anneal the foils were 60°, 105°, 130°, 140°, 155°, and 170°C. The data were then arranged so that the counts for each temperature and the

background could be examined for the seven runs and an average value was calculated and plotted. The results, on Figure IV, are interesting. The background in reference to controls dropped to 69 percent at 155° and decreased rapidly until it was reduced to 54 percent at 170°C. With this rapid falloff at the higher temperature end of the curve the possibility seems to exist (near the melting point at 213°C) that we can achieve an extremely small background, even approaching zero. Further study will be required to examine this possibility and definitely should be carried out for the thought of zero background is titilating indeed.

Plutonium Dosimetry in Bone

There have been some promising steps taken in the effort to achieve more information on the dosimetry resulting from the distribution of plutonium in bone. Dr. John Poston of the Oak Ridge National Laboratory, Health Physics Division, has agreed to furnish us a large quantity of rat bone samples containing widely varying levels of ^{239}Pu. These will be used in the initial phase of the study to establish detectable limits - possibly to lower this limit, to study the ^{239}Pu distribution in rat bone, and to develope a solid detecting procedure to be applied to later samples, i.e. whether to look at alpha tracks, fission fragment tracks, or both, how long should foils be left in contact with the sample to achieve meaningful counts at various specific activities of Pu, etc. Dr. W. D. Norwood, of the U. S. Transuranium Registry, has agreed to supply human bone samples for this work. Herein would be the chance for a significant contribution to present questions being raised concerning the maximum permissible body burden for ^{239}Pu in man which is currently pegged at 0.04μCi. Movements are appearing which, according to the arguments and data subscribed to, speak in favor of keeping the present



Percentage of Background Tracks After Annealing for 20 Minutes at Different Temperatures before Etching

Figure IV

level or lowering it by factors of 200, 10^3, and all the way to 10^5. No one presently knows which level is most appropriate but there does certainly appear to be reason to lower the MPBB by some factor. Solid data leading to a reasonably accurate determination of this value is sorely needed. Any research directed toward this goal should be foremost in the public mind and have its backing considering the accellerating pace of the nuclear power industry, the proposed MOX program and the consequent plutonium wastes.

Counting Uncertainty

Visual counting techniques in general, including the aforementioned two, suffer due to the presence of the human element which can introduce a significant systematic error affecting the accuracy of the final result. For precision work, a great deal of effort must be expended during track counting to insure the elimination of any personal bias which might exist. One assumption applied in this type of counting is the existence of a Poisson distribution describing the counts. This assumption was experimentally checked with data obtained from a series of measurements of one of the background foils. For this measurement, the background tracks were randomly scanned and counted over an area equal to one quarter of the microfiche reader screen. One hundred such random scans and countings were made producing a total of 3514 tracks, yielding a mean value of 35.14 tracks per scan. The frequency histogram, representative of these data is shown on Figure V. The equivalent Poisson distribution is also shown on this figure and is

$$Pn = 500 \frac{m^n e^{-m}}{n!}$$

The normalization constant, 500, is obtained by multiplying five times the number of trials (100) and m is the mean value of the data. The standard

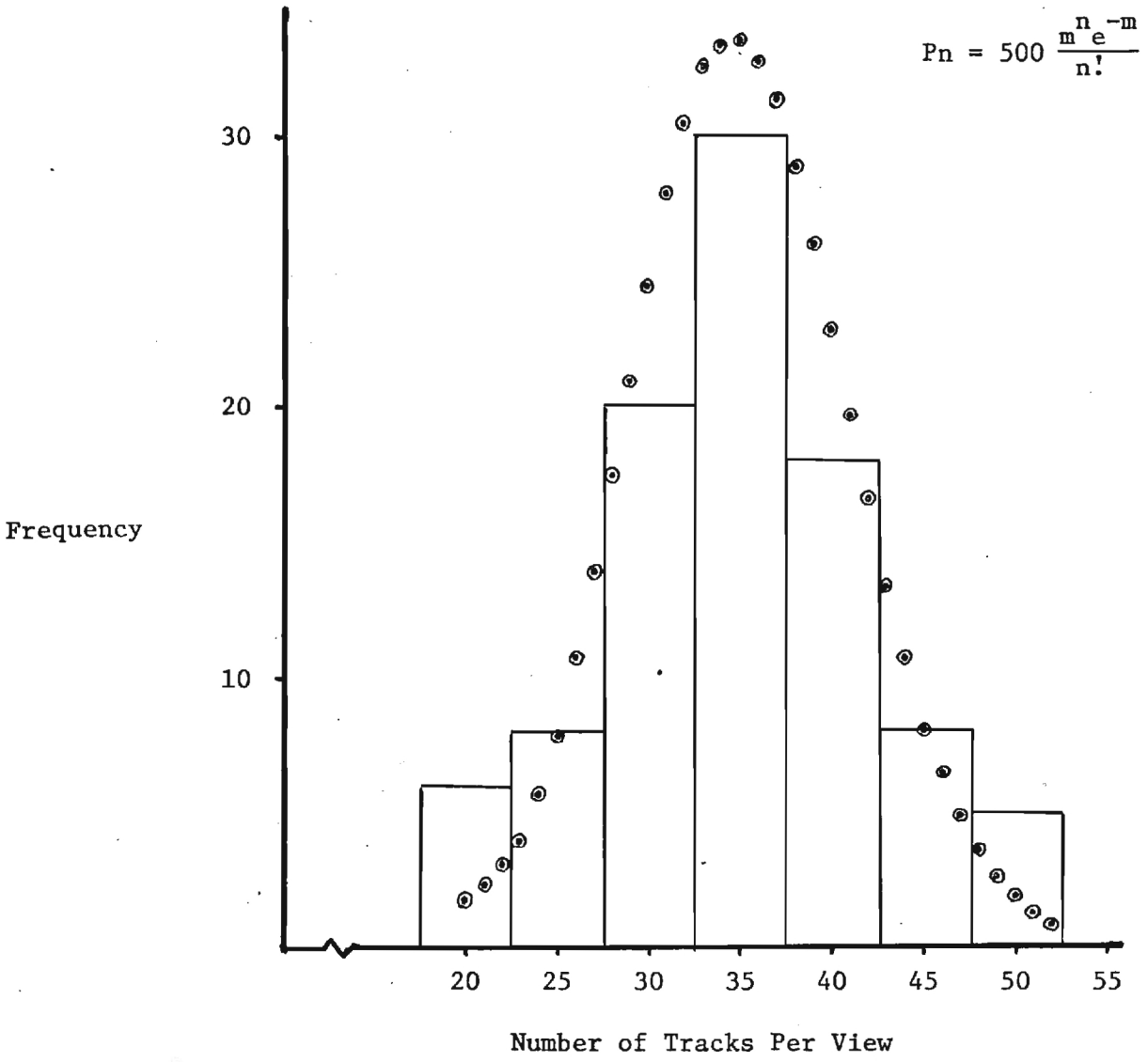


Figure V - Comparison of the Frequency Histogram of Observed Number of Tracks Per View with the Poisson Distribution P_n Corresponding to the Observed Mean Value (m = 35.14)

deviation can be obtained directly from the histogram and is about 7, and the value obtained for the standard deviation directly from the Poisson distribution is $(m)^{1/2} = (35.14)^{1/2} = 5.93 \tilde{=} 6$. Since these two values are so close we can conclude the Poisson distribution assumption employed in the present counting experiments is valid.

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E-26-620

SOME STUDIES ON THE DEVELOPMENT AND APPLICATIONS OF RECOIL PARTICLE TRACK AMPLIFICATION BY ELECTROCHEMICAL ETCHING FOR FAST NEUTRON DOSIMETRY

by

M. Sohrabi and K. Z. Morgan
Co-Principal Investigators

School of Nuclear Engineering
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Atlanta, Georgia 30332

PROGRESS REPORT

on

USERDA Contract No. AT-(40-1)-4814

May, 1976

SOME STUDIES ON THE DEVELOPMENT AND APPLICATIONS OF RECOIL PARTICLE TRACK AMPLIFICATION BY ELECTROCHEMICAL ETCHING FOR FAST NEUTRON DOSIMETRY

by

M. Sohrabi and K. Z. Morgan

Summary

Further studies are reported on the development and application of fast-neutron-induced recoil particle track amplification in polycarbonate foils by electrochemical etching for fast neutron dosimetry. The performance of this dosimetry method for the measurement of fast neutron contamination in the high energy x-ray beams from three medical accelerators was investigated. Neutron dose equivalent ratios as well as their distributions in and out of the beam were determined. Neutron dose equivalent ratios of 0.66 and 1.27 percent were found in the beams of a 25 MeV Allis Chalmers and a 45 MeV Brown Boveri betatron, respectively. The fast neutron dose equivalent ratio in the beam of a Varian Clinac-18 were found to be zero due to insensitivity of this dosimetry approach to the soft neutron spectrum generated in this beam. The values for the two betatrons were in fair agreement with some values reported by other investigators. An electrochemical system was designed and constructed for large-scale neutron dosimetry. It is capable of etching 34 foils (each 2.5 cm in diameter) simultaneously. Improvements were made in the design of the chamber by using fixed stainless steel electrodes on the end walls of the chamber and reduced chamber length. These changes minimized the chamber volume and eliminated the effort of positioning and removing the electrodes each time the chambers are used. Background

track densities in polycarbonate foils of different thicknesses obtained from different vendors are reported also. Masked foils gave the lowest and most reproducible background track densities (on the order of 0.8 ± 0.3 tracks/cm^2). Some further studies on the etching time and thickness dependence of this etching method are given also.

Introduction

This is a short-term progress report on further development and applications of fast-neutron-induced recoil particle tracks in polymers such as polycarbonate amplified by electrochemical etching for fast neutron dosimetry. Briefly, the technique is based on irradiation of a sensitive polymer by fast neutrons followed by an electrochemical etching treatment to reveal the induced recoil and (n,α) tracks. Electrochemical etching, proposed by Tommasino,[1] when applied to recoil particle tracks overcomes many shortcomings of conventional etching methods leading to a new avenue of approach in fast neutron dosimetry.[2,3] Electrochemical etching systems for multiple foil processing were designed and constructed. The electrochemical etching parameters were studied in order to be able to control the sensitivity (tracks/n) and the amplification results, and to better understand the physico-chemical characteristics of this approach.[4,5,6] The dosimetric characteristics of this method such as dose range, neutron energy dependence, fading of tracks, etc. were investigated for fast neutron dosimetry especially for personnel dosimetry.[7,8] The results are all in favor of supporting and using this technique for a number of applications in health physics, radiotherapy, and even radiography. Some of the results were reported in previous progress reports and other publications, some in this report, and some will be studied during the continuation of this project in the coming year.

Results of current studies as reported here are divided into four categories.

(1) To study the performance of this approach under extreme conditions

when the neutron dose is a very small component of the total photon dose. An application of this kind was the measurement of fast neutron dose equivalent and its distribution in and out of high energy x-ray beams from medical accelerators which were, in this case, a Varian Clinac-18, and an Allis-Chalmers 25 MeV betatron and a Brown Boveri 45 MeV betatron.

(2) To develop further an electrochemical etching system to process larger numbers of foils than previously reported.

(3) To study and compare background track densities in polycarbonate foils of different thicknesses purchased from different vendors.

(4) To investigate further some electrochemical etching parameters.

Fast Neutron Dosimetry in High Energy X-Ray Beams of Medical Accelerators

High energy photons are produced by deceleration of high energy electrons generated by medical accelerators when bombarding a metal target. Whenever the energy of the photons or electrons exceeds the (γ,n) and $(e,e'n)$ reaction thresholds of the material impinged upon, neutrons are produced. The common materials used as target, collimator, or beam flattening filter are Cu, Pt, Pb, W, Al, or combinations of them. The cross sections for these reactions are usually relatively low leading to very low fluxes of neutrons compared to very high fluxes of photons. Further, the cross sections for (γ,n) reactions are usually higher than those for $(e,e'n)$ reactions so that neutron flux is usually higher when the machines are operated in the x-ray mode. Thus neutrons contribute a very low fraction of the total photon dose in the beam. Nevertheless, determination of such a low neutron contamination (usually 0.5% of the photon dose) is of some importance to prevent excessive total body irradiation of the patient under treatment and to provide proper shielding of the radiotherapy rooms for the protection of employees. Determination of such a small neutron dose in an intense field of photons was of special interest to us because most of the neutron detection methods fail to perform properly under such extreme conditions. Therefore, the performance of recoil particle track registration was investigated for the measurement of the neutron dose equivalent and its distribution in and out of the beams of three medical accelerators including a Varian Clinac-18 and an Allis-Chalmers 25 MeV betatron both located at Emory University Clinic, and a Brown Boveri 45 MeV betatron located at Atlanta West Hospital, all in Atlanta, Georgia.

A neutron dosimetry method for such an application should meet special requirements including high sensitivity to neutrons and negligible sensitivity to photons, and it is desirable that its response be independent of the post-irradiation time and the neutron energy spectrum. Several investigators have used different approaches for obtaining neutron flux and energy spectrum, dose, or dose equivalent in and out of the beam.[9-13] Activation detectors utilizing gold or indium foils inside spheres of different radii have been used to obtain the neutron energy spectrum of some high energy x-ray beams.[9,10] This approach is post-irradiation time dependent and its response depends on the neutron energy spectrum. A most important limitation in the use of the spheres is that they provide very poor spatial resolution if the neutron beam profile is being measured. Fission fragment registration techniques have also been used for such measurements.[12] The fission fragment registration method shows some photon sensitivity beyond the photo-fission threshold of the fissionable materials. Silicone diodes have been used also for this application in which case the questionable assumption is made that the diodes are insensitive to photons in the beam.[12] As will be discussed below, the results obtained by silicone diodes are higher than any other reported values.

The method of our approach has been recoil particle track registration in polycarbonate foils by electrochemical etching. This method is sensitive to neutrons above an energy threshold (estimated to be 0.7 - 1 MeV) and has negligible post irradiation fading which makes it possible for such dosimetry application to be made by mail. A dose-equivalent response makes it independent of energy spectrum in the beam, and insensitivity to low-LET radiation such as x, beta, and gamma radiation makes it an ideal dosimetry method for measurement of low level fast neutron contamination of high energy x-ray

sources. This method can be considered to be photon insensitive in high energy photon beams:

(1) if the photon dose is below the threshold dose where surface etching would begin to become significant so that some tracks are revealed from deeper layers which increases the sensitivity, and

(2) if the nuclear reactions in the polymer do not increase the number of induced tracks by neutrons produced through photon-neutron reactions in the polymer constituent atoms.

The recoil particle track registration techniques show sensitivity to gamma rays only if the gamma dose is high enough to simulate the critical (or threshold) dose delivered to a polymer by a charged particle around its trajectory. This critical dose is about 7.5×10^6 rads in Lexan polycarbonate calculated by Katz and Kobetich.[14] When the gamma dose approaches such a critical value, then the surface or bulk etching increases revealing more tracks from deeper layers. For example, in this investigation, exposing polycarbonate foils to very high doses of gamma rays from a ^{137}Cs source of the order of 10^4-10^5 rads produced no increase in apparent neutron sensitivity. Only a 25% increase in apparent neutron sensitivity (tracks/neutron) was obtained for Pu-Be neutrons in polycarbonate foils pre-exposed to 6×10^6 rads of gamma rays from the ^{137}Cs source which is close to the critical dose stated above.

Photo-neutrons (γ,n) are produced by photons of energy above 10 MeV in the common elements such as carbon, nitrogen, and oxygen atoms (10.6 MeV for ^{14}N, 15.7 MeV for ^{16}O, and 18.7 MeV for ^{12}C reaching maximum cross sections of about 13 mbarn, 9 mbarn, and 7.5 mbarn at about 23 MeV, respectively).[15] However, due to small cross sections and very small mass of polymer under irradiation, neutron production is negligible and even if they are produced

most of them will escape from the foil site. Therefore, this dosimetry approach was considered totally photon insensitive in this investigation.

The fast neutron dose equivalent measurements were carried out both as a function of photon dose and as a function of distance away from the center of the beam. The dosimeters consisted of a strip of 250 μm masked polycarbonate (50 cm long) placed at a target-to-skin distance of 100 cm, for a 10 x 10 cm field, on the patient table in the plane of the donut. After irradiation was completed, foils corresponding to a given distance away from the center of the beam were cut and etched in a 28% KOH solution at 25°C to which a potential of 800 V at 2 kHz was applied for 4 hours. The neutron dose equivalent (rem) was determined by multiplication of track densities by our track density-to-rem conversion factor (105 tracks/cm^2·rem) reported in a previous study.[8]

Figure 1 shows fast neutron dose equivalent (rem) as a function of high energy photon dose for the two betatrons stated above. According to these data the ratio of dose equivalent of neutrons to that of photons was found to be 0.0060 and 0.0127 (at the center of the beam) for 25 and 45 MeV betatrons, respectively. The equations giving the neutron dose equivalent D_n (rem) as a function of the x-ray dose equivalent D_x (rem) were

$$D_n = 6.00 \times 10^{-3} D_x$$

and

$$D_n = 1.27 \times 10^{-2} D_x$$

for the 25 MeV and 45 MeV betatrons, respectively. Unfortunately, but as might have been expected, this dosimetry approach showed insensitivity to neutrons in the beam of a Varian Clinac-18. This energy, as we have shown, is below the threshold for neutron detection by this dosimetry approach.

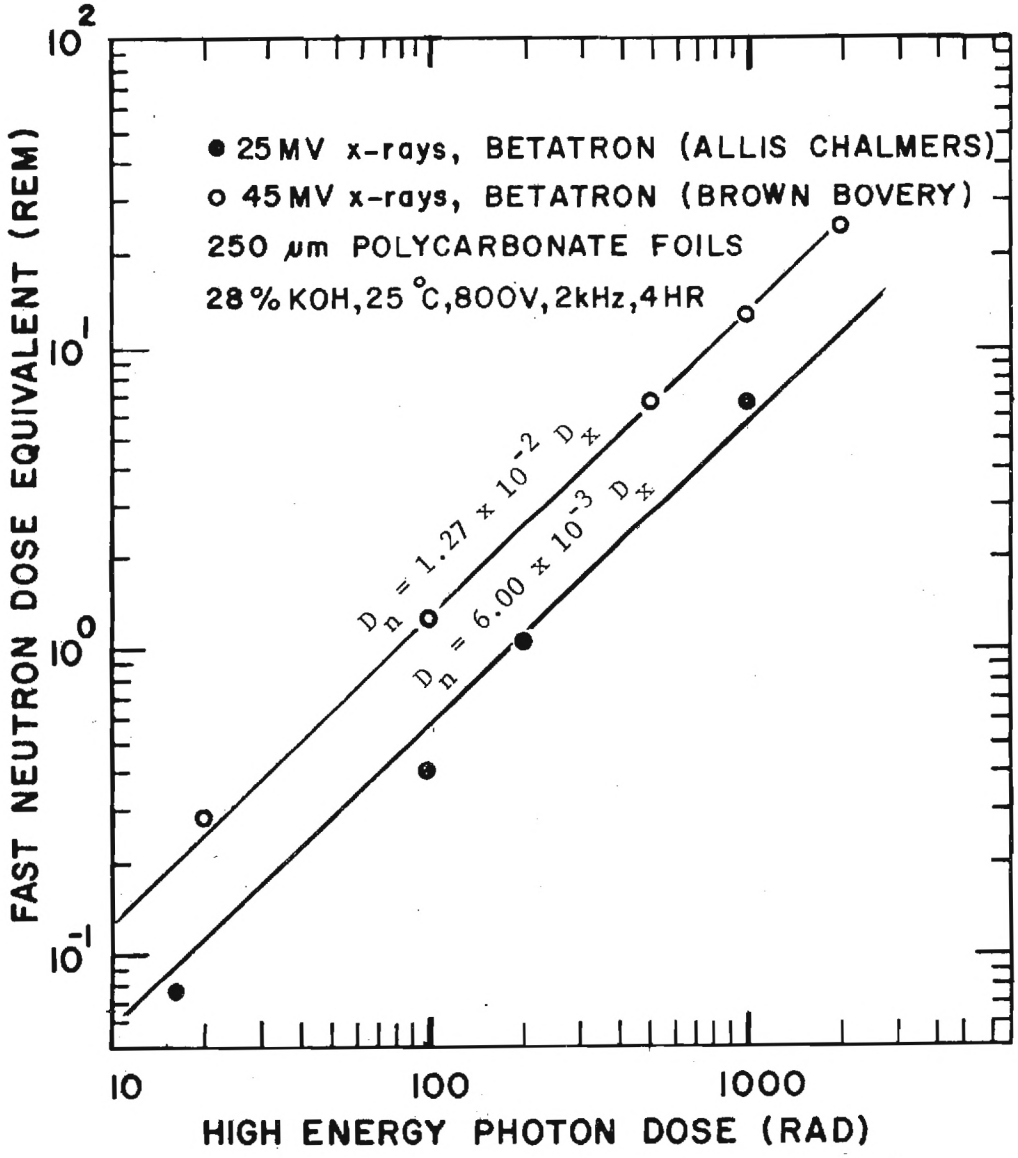

Figure 1. Fast Neutron Dose Equivalent as a Function of High Energy Photon Dose (rad) for 25 and 45 MeV Betatrons Obtained by Recoil Particle Track Registration in 250 μm Polycarbonate Foils (Measurements were made at the center of the primary beam at the patient position.)

Figures 2 and 3 show the percent of fast neutron dose equivalent (compared to that in the central axis) as functions of distance away from the central axis for the 25 MeV and 45 MeV betatrons, respectively. The values were corrected for directional dependence of the dosimeters assuming that all the neutrons originated from the target materials. As can be seen, the fast neutron dose drops rapidly near the edge of the primary beam reaching values of about 10 and 20 percent at 5 cm from the beam edge, respectively, for the 25 MeV and 45 MeV betatrons.

Table 1 compares the results obtained by the recoil particle track registration technique with values reported by other investigators applying other dosimetry methods. Of course, a thorough comparison does not seem feasible because of differences in type and energy of the machines and the dosimetry methods. The dose values of McGinley at al.[13] based on activation of indium foils in a water container might be the best source of comparison since they were determined in the beam of the same machines.

The recoil particle track registration in polycarbonate foils, for reasons stated above, failed to measure the neutron dose equivalent in the beam of the Varian Clinac-18. The reported value of zero (see Table I) is not correct and merely indicates the fast neutron dose above the threshold is zero. The value obtained by the activation method is closer to the actual value. As can be seen in Table I, the neutron dose equivalent ratio in the beam of the Allis-Chalmers 25 MeV betatron is about the same as the value by the activation method within ± 10%. However, the ratio out of the beam is about four times smaller by this method of dosimetry compared to the activation method. Comparing the data of the 45 MeV Brown Boveri betatron, the ratios are about twice larger (in the beam) and four times smaller (out of the beam). By looking at the ratios, it seems that this activation method

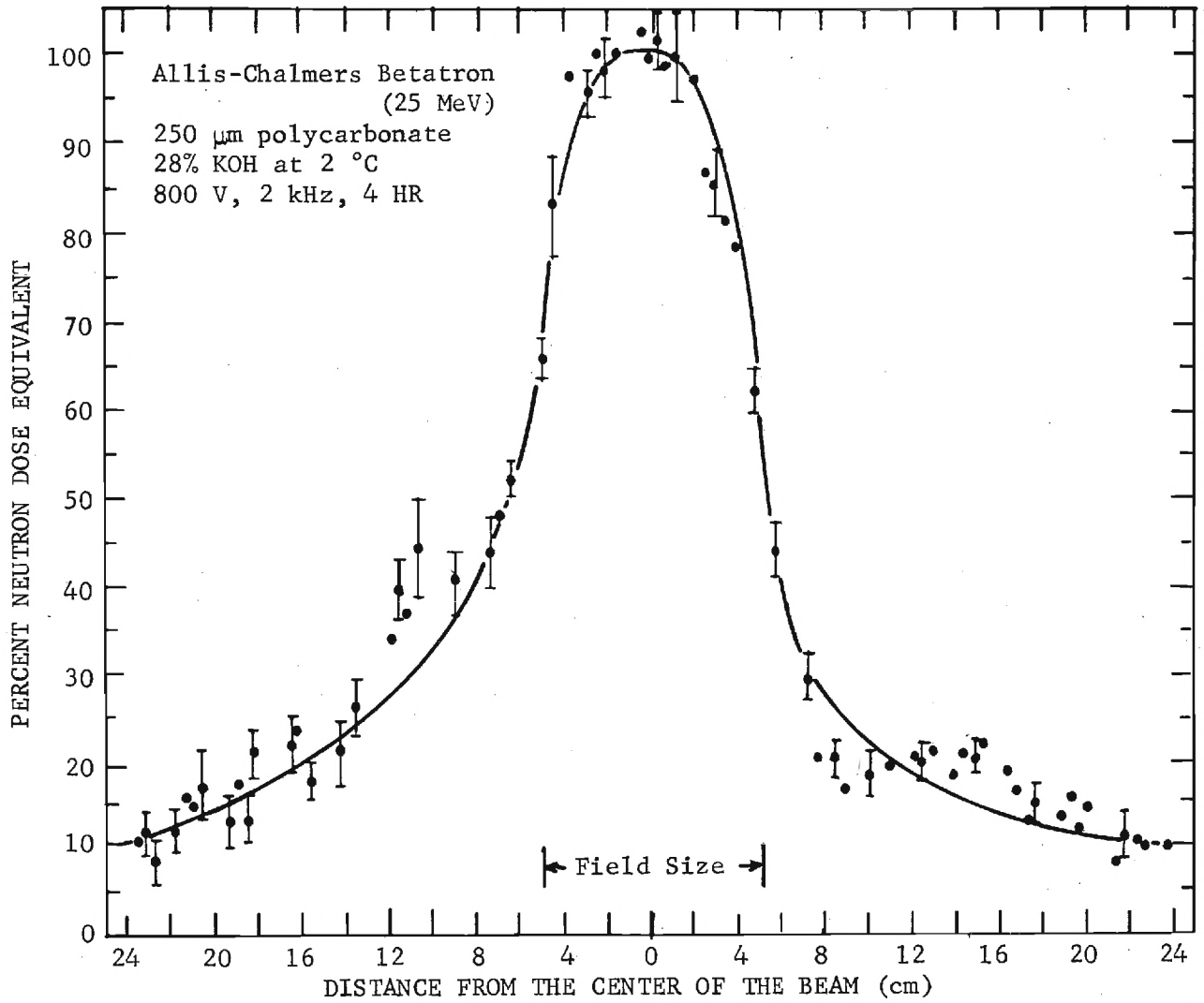

Figure 2. Percent Neutron Dose Equivalent as a Function of Distance Away from Central Axis in the High Energy X-Ray Beam of an Allis-Chalmers 25 MeV Medical Betatron (TSD = 100 cm, 10 x 10 cm field)

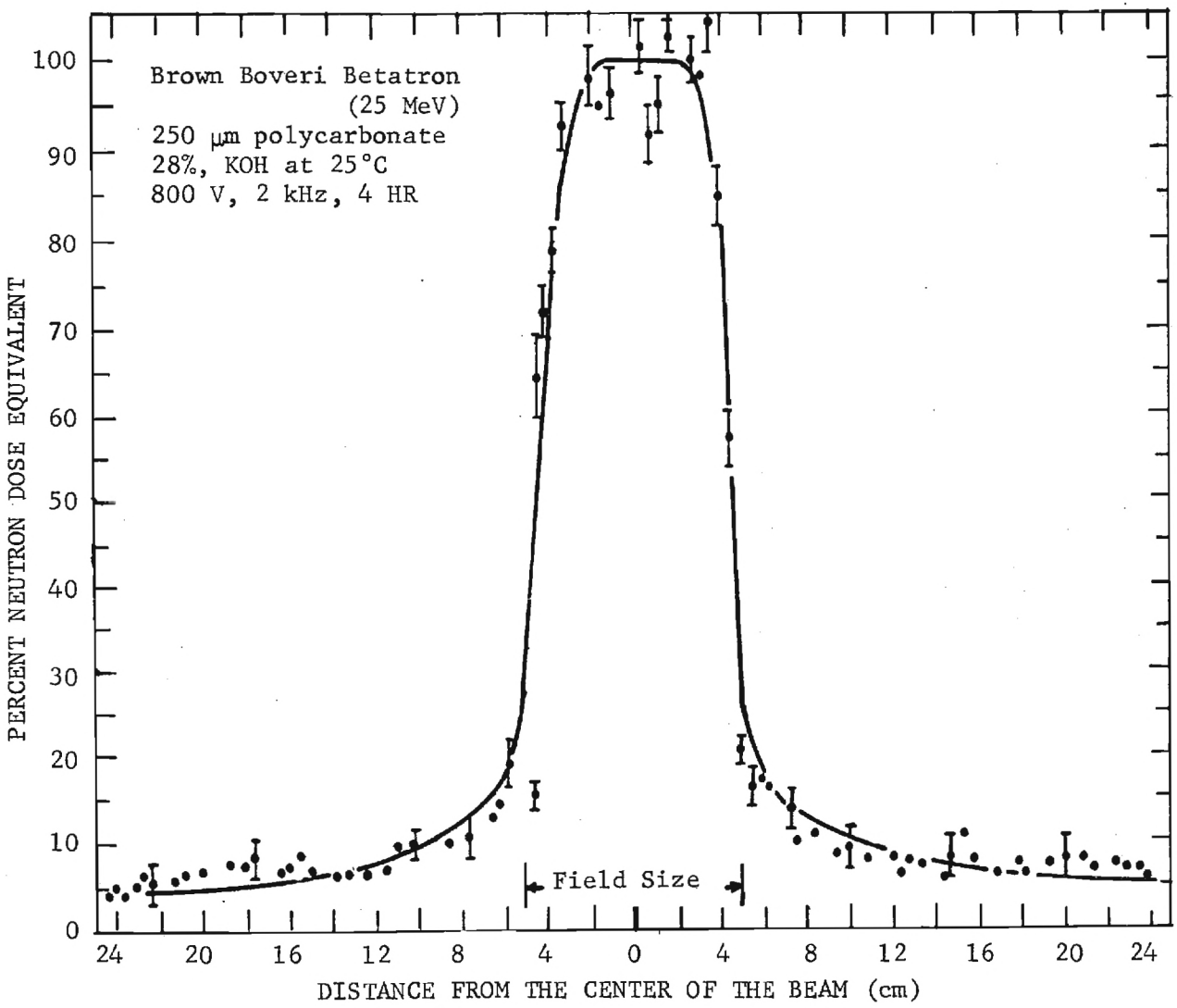

Figure 3. Percent Neutron Dose Equivalent ás a Function of Distance Away from Central Axis in the High Energy X-Ray Beam of a Brown Boveri 45 MeV Medical Betatron (TSD = 110 cm, 10 x 10 cm field)

Table 1. Comparison of Neutron Contamination of Different High Energy X-Ray Beams in Some Medical Accelerators

Investigation by	Accelerator	Energy (MeV)	Mean Neutron Energy (MeV)	TSD (cm)	X-Ray Field Size (cm x cm)	Neutron Detection Method	Neutron Dose Equivalent to X-Ray Dose	
							Center of the Beam	5cm Outside the beam edge
Axton and Bardell (1972)[9]	Brown Boveri Betatron	35	Estimated: in the beam(< 3) out of the beam (1.3)	-	-	Gold Activation in a Polyethylene Sphere (20 cm)	0.0062	0.0017
Axton and Bardell (1972)[9]	M.E.L. Equipment Co. Ltd.	16	Estimated: in the beam (0.8) out of the beam (0.75)	-	-	Gold Activation in a Polyethylene Sphere (20 cm)	0.0053	0.0025
Axton and Bardell (1972)[9]	Based on Calculation of Barber and George(quoted in 9)	25	-	-	-	Calculation	0.013	Calculated Upper Limit Values
		30	-	-	-		0.016	
		35	-	-	-		0.015	
Briden and Ice (1972)[10]	Betatron	25	~2	-	-	Gold Activation in Polyethylene Spheres	0.002	-
Wilenzick et al (1973)[12]	Sagittair Linac	25	~2	100	10x10	Fission Track Detectors and Silicone Diodes	0.047	0.0073
Wilenzick et al (1973)[12]	Siemens Betatron	19	Estimated: 1.5	50	7.6x11.4	Fission Track Detectors and Silicone Diodes	0.023	0.0047
McGinley et al (1976)[13]	Varian Clinac-18 Linac	10	Estimated: 0.5	100	10x10	Indium Foil Activation in a Water Container	0.00042	0.0006
This Research						Polycarbonate Recoil Particle Track Dosimeter	Zero	Zero
McGinley et al (1976)[13]	Allis Chalmers Betatron	25	~2	100	10x10	Indium Foil Activation in a Water Container	0.0054	0.0040
This Research						Polycarbonate Recoil Particle Track Dosimeter	0.0060	0.0013
McGinley et al (1976)[13]	Brown Boveri Betatron	45	Estimated: >3	110	10x10	Indium Foil Activation in a Water Container	0.0057	0.0040
This Research						Polycarbonate Recoil Particle Track Dosimeter	0.0127	0.00127

has overlooked the neutron spectra and not taken adequate account of the difference in neutron energy distributions in and out of the beams of these two betatrons leading to what we believe may be an erroneous conclusion that there are equal dose ratios for both machines in and out of the beams.

The neutron dose equivalent ratios for the 25 MeV Allis-Chalmers betatron obtained in this investigation are in fair agreement with the ratios of Axton and Bardell[9] (i.e. the 35 MeV Brown Boveri betatron)[9] both in and out of the beam assuming that they used a TSD of 100 cm. It is also three times larger than the ratio obtained from the reported values of Briden and Ice[10] for a 25 MeV betatron. These ratios are about 14 times (in the beam) and 7 times (out of the beam) smaller than the ratios reported by Wilenzick et al.[12] The dose equivalent ratios obtained from the data of Wilenzick et al. have higher values for both machines they studied. It seems that besides their fission fragment registration method which was corrected for its (γ,f) sensitivity, the silicone diodes used in their investigation might have responded to photons too, unless their machines have special construction materials leading to such high neutron contamination. Nevertheless, their data are consistent with those of Robinson and Kehrer (quoted in reference 12). Further, the dose equivalent ratio of this investigation for the 45 MeV Brown Boveri betatron agrees with the calculated upper limit of dose equivalent rate reported by Axton and Bardell.[9]

To conclude, the consistency obtained by comparing the results of this investigation with some of the others is in favor of using this dosimetry technique for such applications. Especially, this comparative study is an indication of total insensitivity of the recoil particle registration technique to high energy photons.

Background Track Density Comparison

The polycarbonate dosimeters as used in these investigations are foils of 2 to 10 cm in diameter having thicknesses from 75 to 500 μm. They are fairly rugged and can be prepared by punching or cutting them from a sheet of polycarbonate foil. Care should be taken in punching and handling the foils. Punching and hammering on the die causes (in some cases) an increase in track counts with some local spots having high track densities. The prepared foils do not usually need extra support as is required in thin foils (e.g., 6-12 μm) used for spark counting as mentioned earlier. However, foils should be protected from any scratching processes which will be amplified by electrochemical etching. Masked foils minimize the flaws such as foil cracks and scratches and placing the foils in a badge suffices their protection.

Polycarbonate sheets are commercially available and can be purchased from many vendors at reasonable cost so that cost per foil is about nil. Care should be taken in choosing the right material in terms of uniformity in thickness, reproducibility in obtaining the same material during different purchasing periods, as well as obtaining foils with nil or uniformly low background. Table 2 shows background count density of different polycarbonate materials obtained from various vendors. The total etched area for this background density determination was 150 cm^2. Both masked and unmasked foils were used for this study. As was expected, masked foils have the lowest background count density with good reproducibility from one spot to another. However, in unmasked foils, a low background cannot be guaranteed since mishandling of the foils during packaging and shipment, punching or cutting the foils, etc. will increase this background count density significantly.

Table 2. Background Track Density in Different Polycarbonate Foils Electrochemically Etched

Type of Foil	Manufacturer	Thickness	Etching Conditions	Background Track Density (Tracks/cm^2)
Polycarbonate (unmasked)	West Lake* Plastics	250 μm	28% KOH Solution at 25°C, 800 V at 2 kHz for 4 Hours	126 ± 58
Polycarbonate (unmasked)	General+ Electric	250 μm	28% KOH Solution at 25°C, 800 V at 2 kHz for 4 Hours	33 ± 10
Polycarbonate (unmasked)	Rowland @ Products	250 μm	28% KOH Solution at 25°C, 800 V at 2 kHz for 4 Hours	11 ± 3
Polycarbonate (masked)	Rowland @ Products	250 μm	28% KOH Solution at 25°C, 800 V at 2 kHz for 4 Hours	0.8 ± 0.3
Polycarbonate (unmasked)	Rowland @ Products	375 μm	28% KOH Solution at 25°C, 800 V at 2 kHz for 12 Hours	4 ± 1
Polycarbonate (masked)	Rowland @ Products	500 μm	28% KOH Solution at 25°C, 800 V at 2 kHz for 16 Hours	6 ± 2

* Westlake Plastics Company, Lenni, Pa.
\+ General Electric Company, Atlanta, Ga.
@ Rowland Inc., Kensington, Conn.

Individual calibration of each batch of polycarbonate even from the same manufacturer is recommended since some variations in sensitivity have been observed by purchasing the material in different periods.

Many attempts were made to treat these background tracks. Annealing them at higher temperatures such as at 100°C developed some pin-head holes in the foils which resulted in stopping the electrochemical etching process after a short period of etching. Other approaches such as annealing the foils in boiling water for a period of 4 hours or pre-etching of the foils in 28% KOH at 60°C for 2 hours (conventional etching) prior to electrochemical etching did not lead to any significant improvements in this preliminary study. Based on these limited investigations, the masked foils with some precaution in handling before etching seem to be the best approach.

Electrochemical Etching Systems

Improvements were made in the design of the electrochemical etching chambers used in our previous study. The length of the chamber was reduced from 22cm to 9cm using fixed stainless steel electrodes at the end walls of the chamber. This design minimizes the volume of the etchant as well as efforts of placing and removing the electrodes before and after etching respectively. Two wire jacks can be located on top of each electrode for high voltage connection.

One chamber was constructed to etch one foil with an effective area of $50cm^2$. Such a chamber is of immediate interest for neutron radiography applications and for accurate low neutron dose measurement. This chamber was used in some preliminary tests for neutron radiography of some small objects.

Two additional chambers were constructed, one with a capacity of processing 7 foils (each 2.5cm in diameter) and the other 34 foils simultaneously.

Figure 4 shows a photograph of the latter chamber with fixed stainless steel electrodes (24.5cm in diameter and 75 μm in thickness) and 10cm total length. The diameter of the chamber is 25.5cm. There are two holes in the bottom connected to two hoses for draining. This chamber did not give the complete assurance for sealing and electrically isolating the two parts of the chamber for reproducible etching in terms of leakage of etchant during the etching process.

Among the two power supply systems previously reported, the power generated by a Heathkit audiogrequency generator (No. 1G-72) the output of which is amplified by a Heathkit push-pull amplifier followed by further amplification through an audiotransformer is capable of supplying the necessary power for this large chamber.

Some Observations on Electrochemical Parameters

The polycarbonate foil thickness is a parameter of importance in affecting the electrochemical etching amplification results in terms of sensitivity (tracks/neutron) and track diameter.[6] As the thickness of the foils increases the sensitivity decreases and the mean track diameter increases. About 100 times reduction in sensitivity (from 4.0×10^{-6} to 4.0×10^{-8} tracks/neutron) and about 4 times increase in mean track diameter (from 45 μm to 210 μm for Pu-Be neutrons) were obtained when polycarbonate foil thickness was doubled from 250 m to 500 m both etched in 28% KOH at 25°C when applying 800 V at 2 kHz for 5 and 21 hours, respectively. It was found that such a low sensitivity in 500 m foils can be compensated by applying 2000 V at 2 kHz, leading to a current of about 3.5 mA. Applying this voltage, a neutron sensitivity in the order of 1.0×10^{-6} was obtained which is about 25 times larger than the above given value for this thickness under the applied etching conditions. This

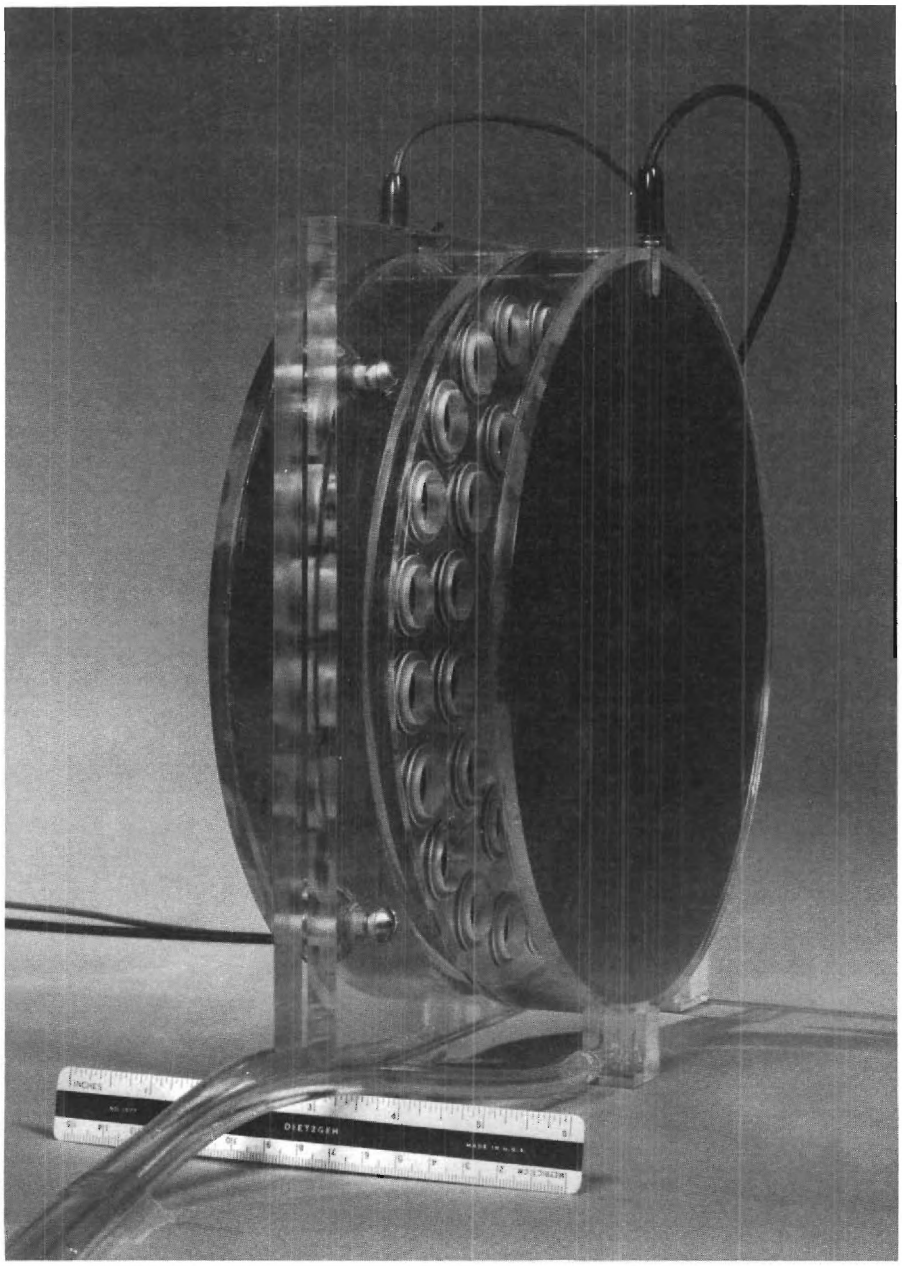

Figure 4. An Electrochemical Etching Chamber with Reduced Length and Fixed Stainless Steel Electrodes with a Capacity to Etch 34 Foils Simultaneously

sensitivity, however, is still about 25 times smaller than that given for 250 μm foils while the track diameters are larger, making track density determination much simpler at low magnifications.

In track etching, it is common that as the track density increases beyond a certain value, depending on the etching method and the applied etching conditions, type of foil, and charge particle and its energy, there would be a tendency to overlap the tracks. In electrochemical etching, it was interesting to observe that at high track densities close to the overlapping point, tracks change their shape depending on the track density. If tracks are distributed with enough spacing between them, they appear perfectly round. At high track densities corresponding to doses in the order of 500 rads, for example, tracks form different shapes (e.g. squares, triangles, segments of a circle, etc.) which minimizes overlapping. There is also a tendency that mean track diameter decreases with the increase in track density. Mean track diameters corresponding to doses up to 1000 rads were determined which confirmed this interesting observation. Decreasing the etching time also prevents complications of track density determination at high doses on the order of 1000 rad. For example, for 250 μm polycarbonate foils, 2 to 3 hours of etching extend a linearity for dose response up to 1000 rad. As the etching time increases, track diameter increases which makes overlapping possible, leading to a deviation from the linear dose response.

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Acknowledgements

The authors of this report wish especially to acknowledge the valuable contributions in these studies of neutron contamination of medical x-ray beams by Dr. P. H. McGinley who, since this research began, now shares joint faculty appointment at Emory University and our university, Georgia Institute of Technology.

E-26-620

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GEORGIA INSTITUTE OF TECHNOLOGY
ATLANTA, GEORGIA 30332

OFFICE OF
THE DIRECTOR OF
FINANCIAL AFFAIRS

March 1, 1977

United States Energy Research and
Development Administration
Oak Ridge Operations
Contract Division
P. O. Box E
Oak Ridge, Tennessee 37830

Attention: Mr. A. H. Frost, Jr.

Reference: Contract Number EY-76-S-05-4814;
formerly E-(40-1)-4814

Gentlemen:

Enclosed in triplicate are the Statement of Costs for Contract Number EY-76-S-05-4814, formerly E-(40-1)-4814, covering the contract periods September 1, 1975 through August 31, 1976 and September 1, 1976 through November 30, 1976.

If you have questions or desire additional information, please let us know.

Sincerely yours,

C. Evan Crosby
Associate Director of
Financial Affairs

CEC/bs
enclosures:
cc: Dr. K. Z. Morgan
Dr. L. N. Weaver
Mr. E. E. Renfro
Mr. A. H. Becker
File E-26-620
File E-26-623

GEORGIA INSTITUTE OF TECHNOLOGY, ATLANTA, GEORGIA
U. S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
STATEMENT OF COSTS

1. Name and address of Contractor: Georgia Institute of Technology
Atlanta, Georgia 30332

2. Contract Number: E-(40-1)-4814

3. Beginning and ending date of pertinent contract period: September 1, 1975 thru August 31, 1976

4. Costs incurred during the pertinent contract period:

a. Salaries and Wages	$ 18,552.32
b. Travel (all domestic)	850.16
c. Other direct costs	2,472.83
d. Total direct expenditures	$ 21,875.31
e. Indirect Costs - 68% of Salaries & Wages	12,615.58

5. Total costs for the pertinent contract period $ 34,490.89

6. Support Cost for the pertinent contract period. Using the percentage of 100% as set forth in Appendix "A" the amount chargeable to ERDA would be $34,490.89. $ 34,490.89

7. Cumulative support cost 64,778.67

8. Accumulated support ceiling 64,871.00

9. Unexpended ERDA funds $ 92.33

I hereby certify that this report is true and correct to the best of my knowledge and belief and that the costs listed herein were incurred in connection with the performance of the research provided for under the contract and in accordance with the terms and conditions set forth therein.

K. Z. Morgan, Professor of Nuclear Engineering
Name and Title of Principal Investigator

Signature

February 23, 1977
Date

C. Evan Crosby, Associate Director of Financial Affairs
Name and Title of Business Officer

Signature

3/1/77
Date